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14. ABSTRACT

This report results from a contract tasking QinetiQ Ltd as follows: The Grantee will investigate the effects of synergistic and incongruent tactile and visual information on a representative flight task. The task will be related to maintaining correct spatial orientation and recovering from spatial disorientation. Subjects will be asked to perform a primary (flying) and secondary (non-flying) task with and without tactile orientation information to determine the advantages and disadvantages of using both tactile and visual orientation information. The specific questions that must be answered are: 1) what are the interactions between visual and tactile stimulation, 2) how does tactile information aid or detract from information presented in the other sensory modalities - specifically visual for this preliminary study, and 3) can any performance enhancement be gained by combining multisensory information.

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QinetiQ

Understanding Multisensory Integration for Pilot Spatial Orientation

Dr Ian R. Moorhead, Dr Sharon Holmes and Alistair Furnell
QINETIQ/KI/CHS/TR042277
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Declaration

(1) In accordance with Defense Federal Acquisition Regulation 252.227-7036, Declaration of Technical Data Conformity (Jan 1997),

"The Contractor, QinetiQ, Ltd., hereby declares that, to the best of its knowledge and belief, the technical data delivered herewith under Contract No. FA8655-03-1-3048 is complete, accurate, and complies with all requirements of the contract.

DATE: 28th September 2004

Name and Title of Authorized Official: Dr Ian R. Moorhead

(2) In accordance with the requirements in Federal Acquisition Regulation 52.227-13, Patent Rights-Acquisition by the U.S. Government (Jun 1989),

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Executive Summary

This document is the final report on research carried out by QinetiQ, Centre for Human Sciences on behalf of the European Office of Aerospace Research and Development under contract No. FA8655-03-1-3048.

The research was aimed at a preliminary investigation into whether the provision of vibrotactile signals might benefit pilots who were experiencing spatial disorientation.

The objectives were to: -

- Determine experimentally whether, and by how much, a tactile signal can benefit an individual carrying out a high workload visual task.
- Determine and quantify the effects of congruent and incongruent tactile-visual information on performance.
- Ascertain if any beneficial effect is as a result of true multisensory integration or whether it is a simple alerting (attention grabbing) effect.

We have used a simulation of a pilot activity in order to investigate these issues. Subjects carried out a visual alphabet arithmetic task along with a simultaneous visual tracking task. The tracking task was completed with no tactile cueing, or augmented incongruent or congruent tactile cueing. The results demonstrated that providing subjects with a tactile stimulus whilst undertaking visual tasks does not distract a subject from these main visual tasks. This is evidenced by the maintained performance in the alphabet calculation task, across all of the experimental conditions.

Tactile cueing did provide a benefit in terms of response time in reacting to the tracking task. Response times with tactor support were approximately twice as fast compared with no tactor support. In addition, there was a much-reduced variability in response times with tactor support compared with none.

Small differences in congruent and incongruent tactor cueing were observed in the data from the first experiment. The second experiment demonstrated that the main effect of the tactor was to act as a cue to the track being lost, i. e. as an attention grabbing mechanism. There was no direct benefit due to the lateralisation of the cue.

Overall the results showed that subjects were able to increase the number of tracking corrections without any detriment to the high demand cognitive task, when tactor cueing was used. One might therefore infer an increased capacity as a result. The results support the concept of using a tactor system as a method of aiding a pilot by reducing workload and improving performance by producing faster and more consistent reaction times. Tentatively, the results suggest that tactile systems may reduce the risk of pilot spatial disorientation by two methods. Firstly, by reducing primary task load, enabling improved performance on a secondary task (e.g. target acquisition). Secondly, by providing an attention-grabbing mechanism for pilots who have become spatially disorientated and are unaware of the fact (Type I SD). However, there are still many human factors issues regarding the integration of tactile systems for pilots that require further, systematic investigation.

We recommend that further work should be undertaken to investigate the benefits identified in this study. A suitable environment in which to undertake such studies would employ immersive simulation to increase the ecological validity of the task, whilst maintaining experimental control. An ideal test-bed for this kind of approach would be a Cognitive Cockpit environment.

List of contents

1 Introduction

1.1 Background

This document is the final report on research carried out by QinetiQ, Centre for Human Sciences on behalf of the European Office of Aerospace Research and Development under contract No. FA8655-03-1-3048.

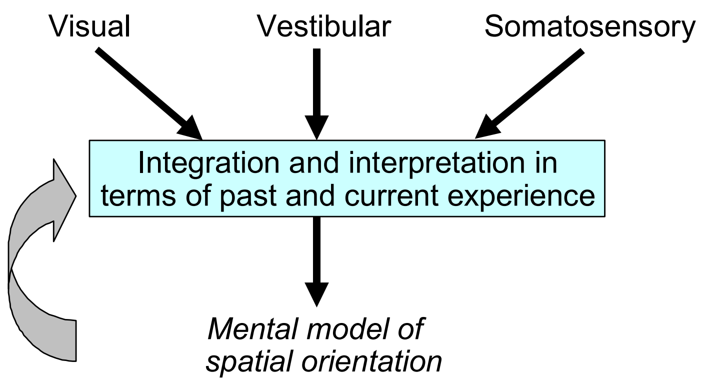
Spatial disorientation is a major cause of both military and civilian aircraft accidents [1]. It was a major contributory factor in 30% of all US Army rotary-wing accidents which occurred between 1987 and 1995, and which were graded as class A[1]. Accidents arising from spatial disorientation were more severe than those not involving spatial disorientation, with 36% of accidents in Class A compared to 18% of non-disorientation accidents. In the 10-year period between 1991-2000 inclusive, spatial disorientation was the cause, or a major contributory factor, in 20% of USAF accidents, at the cost of 60 aircrew lives and $1.4B.

Clearly, there is value in both humanitarian and financial terms of investigating methods that reduce the likelihood of spatial disorientation. At present, all orientation information is presented to the pilot visually. This modality is particularly susceptible to becoming overloaded, leading to a loss of [correct] spatial orientation.

Since humans have evolved to integrate information from multiple senses, to support decisions on orientation, there might me a way of reducing loss of correct spatial orientation. This report presents the results of a preliminary study, which investigated whether using a combination of visual and tactile information would improve pilot performance and reduce the risk of spatial disorientation.

1.2 Spatial Disorientation in Aircraft

Accurate perception of orientation within the external world is achieved by the combined use of visual, vestibular and somatosensory information [2]. This sensory information is compared to previous experience, and a mental model of the orientation and position of the individual in the external world is formed (see Figure 1-1). Vision is the key sense for orientation, and normally acts as a frame of reference for the interpretation of information from the non-visual senses.



[1] A Class A accident is defined to be an accident that results in fatality or total permanent disability, loss of an aircraft, or property damage of $1 million or more.

Figure 1-1 Representation of the sensory inputs and processes for spatial orientation

Aircraft, both rotary and fixed-wing, can create dynamic environments in which it is difficult for the pilot to maintain the correct spatial orientation, or where it is difficult for the pilot to regain the correct orientation when it is lost [3]. Without adequate visual cues, a condition that can occur when flying, during instrument meteorological conditions (IMC) or at night, the dynamic environment of the aircraft may induce an erroneous perception of orientation. For example, a helicopter might drift or rotate during a hover manoeuvre, but the movement may be below the detection threshold of the vestibular system of the pilot. Without the concomitant visual motion cues, the sub-threshold linear drift or rotation of the helicopter may lead the pilot to believe he or she is maintaining the same position and heading, when in fact the aircraft may have side slipped or be facing in a different direction.

Inadequate or erroneous visual cues alone can also cause spatial disorientation. For example, judging height can be difficult when flying over featureless terrain such as a sandy desert, due to the lack of texture cues [4]. The assumption that cloud tops are always horizontal may cause disorientation when they are not actually horizontal [5]. In this situation, the dynamics of the flight manoeuvres give rise to accelerations which, when combined with gravity, feel like gravity alone to the pilot, but are no longer indicative of the true vertical. Such sensations also occur in turns and manoeuvres that involve deceleration or acceleration in the line of flight [6].

Spatial disorientation can also occur if the pilot has been engaged in a secondary task, where distractions could cause the pilot to miss vital flight data from instruments [7].

When flying in conditions of poor visibility, such as in cloud or at night, the only visual orientation reference may be the environment of the cockpit. In these situations pilots become heavily reliant on information from instrument panels, night vision devices, and from helmet-mounted and head-up displays, to maintain spatial orientation. Any kind of distraction from these tasks may result in missed changes in aircraft orientation information. Figure 1-2 illustrates, within the cognitive framework of figure 1-1, how information from flight instruments is utilised for determining pilot spatial orientation.

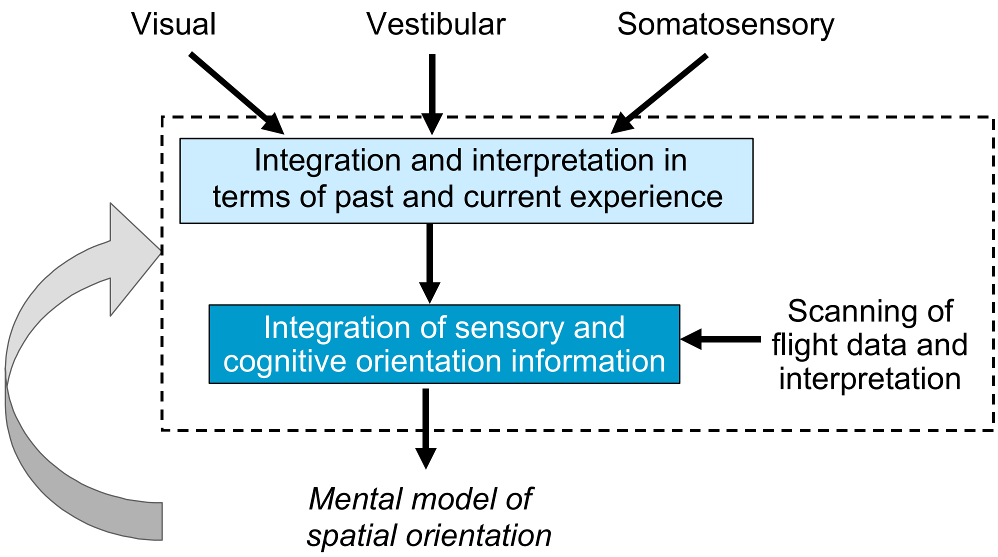


Figure 1-2 Illustration of how sensory information and data gained from flight instruments determine pilot spatial orientation

Although most military aircrew receive some form of spatial disorientation training (lectures and/or ground-based demonstrations, and/or in-flight demonstrations) the rate of aircraft accidents attributable to SD does not appear to be diminishing. For example, SD has been cited as a main causal factor in 4-5% of US military aircraft accidents (Army, Navy and Air Force) over the last 5 -10 years [8].

Conveying aircraft orientation cues by a more intuitive method than the current interpretation of visual displays may be of benefit in reducing spatial disorientation by augmenting sensory information. Intuitive cues may not only enable a rapid recovery of the aircraft from an unusual attitude but may also reduce the likelihood of this situation arising in the first place, by improving the ease by which pilots maintain their mental model of aircraft orientation. This could be achieved by either using these cues to reduce visual and mental workload on secondary tasks, therefore freeing resources for frequent and adequate scanning of instruments, or as an orientation aid *per se*.

Research into alterative means of conveying aircraft orientation information has been underway for some years. These include the use of the auditory modality, such as 3D audio cues [9] and more recently, the somatosensory sense via the use of tactile devices [10]. For the purposes of this study and report, the latter will be further described and examined.

Tactile aids to flying, such as the Tactile Situation Awareness System (TSAS), developed by the Naval Aeromedical Research Laboratory, have been shown to effectively aid the pilot's maintenance of situation awareness and the correct spatial orientation [11, 12, 13]. Tactile aids to flying offer the possibility of reducing the risk of developing SD in-flight in the following three ways. Firstly, tactile information could be highly intuitive, and therefore require less cognitive processing or could be learned to a level where their processing is automatic. As such, they might therefore help reduce visual workload during high workload situations such as that encountered during air-to-air combat by moving the task into a separate sensory modality. Secondly, tactile aids have been shown to vastly improve the detection of changes in aircraft attitude that occur at when the movements are insufficient to stimulate the vestibular system (passive somatogravic illusions, e.g. undetected drift of rotary craft). This benefit could also transfer to fixed-wing aircraft reducing the incidence of both passive and active somatogravic illusions (the latter are generated by supra-threshold vestibular stimulation, such as acceleration in fixed-wing aircraft that could otherwise lead to a false sense of pitch up). Finally, tactile aids have been shown to enable pilots to recover from unusual attitudes to straight and level flight in the absence of flight instruments [11]. Overall, tactile aids that relay spatial orientation information may reduce the risk of unrecognised, Type I SD (first and second points above) and improve recovery from recognized, Type II SD (third point).

While demonstrations and trials of tactile aids in-flight and in simulator environments have illustrated their effectiveness at reducing the risk of SD, fundamental human factors research to quantify and understand the mechanisms that might give rise to benefits has not been fully conducted. Existing and previous research programmes, centre on implementation details such as tactor placement, number of tactors, frequency of tactor vibration, and duration of vibration for the optimum relay of tactile information in stationary situations [14]. A number of fundamental questions about multisensory integration still require investigation.

This report summarises preliminary experiments to examine the following:

- How is sensory information attenuated in high-workload situations?
- If the information is congruent[2], does this result in improvements in performance?
- If the information is incongruent, does this increase workload and result in decrements in performance?
- In a multi-sensory situation, which sense dominates?

The remainder of the report is organised as follows:

Section 2 provides a short review of current understanding of multisensory integration from a neurological and psychological perspective along with a review of recent related work on tactors. Section 3 provides a description of the scoping experimental programme we have undertaken in an attempt to address some of the above questions, and section 4 provides a summary of the conclusions and recommendations for future work. Appendix A comprises a summary of a literature review carried out on tactor threshold studies.

[2] Throughout the report we will use the words congruent to signify inputs to the somatosensory system that are on the same lateral aspect as the visual information, and incongruent to refer to inputs that are on the opposite side.

2 Multisensory Integration

2.1 General

Multisensory integration is one of the many tantalising capabilities of the human (and presumably animal) brain. Many ordinary events in the physical world – the scent from a vase of flowers, the sound of a car passing by, the feeling of a handshake, the sight of a tree blowing in the wind – produce signals in several sensory modalities simultaneously. Although much information about such events can be extracted by treating these signals one modality at a time, it is clear that the brain, by integrating across sensory modalities, achieves a sum, which is greater than the parts. Our brain is exquisitely attuned to multisensory correlations, which it uses to modulate and refine perceptual analysis.

There are numerous examples of how perception can be enhanced, but also biased, by the integration of sensory signals across modalities. For example:

> Low contrast or noisy visual and sound stimuli can be combined to improve spatial localisation. On the other hand a salient visual stimulus can readily "capture" the perceived origin of a sound, as occurs when we view a ventriloquist [15].
>
> Being able to see ones arm improves the spatial resolution of tactile discrimination when two (unseen) pinpoint stimuli are applied near one another on the skin [16].

These, and many more examples underscore the importance of multisensory integration in assisting perceptual decisions.

2.2 Neurobiology of Multisensory Integration and Sensory Maps

Classically, cross-modality effects have been attributed to neuronal interactions in multisensory convergence areas of the brain such as the superior colliculus [16] or the parietal lobe [17]. However, more recently, with the advent of functional magnetic resonance imaging (fMRI) this traditional view has been questioned. Multisensory effects have been isolated in auditory [18] and visual [19] cortices. These lines of research are new, and it is not yet clear what the mechanism is by which a tactile stimulus is able to exert a modulation on visually evoked activity in the occipital cortex. There appears to be a general design principle within the brain by which not only are their forward projections starting at the sensory inputs, but there are also back-projections from higher areas towards the sensory inputs [20].

An additional challenge for understanding how multisensory integration occurs is to determine what neural computations are required and in particular how the different "maps" for the different senses are combined. Visual, auditory and somatosensory stimuli are represented by different topographic arrangements in their in their respective cortical areas. This is primarily because each sensory map is organised according to the geometry of the corresponding receptors. The bite of a mosquito on ones hand is represented in the somatosensory cortex in a skin-based frame of reference, whereas our visual image of the mosquito biting is coded in a retinal frame of reference. Not only are these maps different geometries but each is also distorted according to the relative importance (as measured by cortical area) of different parts

of the sensory surface. Thus in the visual map, considerable brain area is allocated to processing the central (foveal) region. The relative representations of different parts of the body are shown in figure 2-1 and the proportion of cortex devoted to different parts of the visual field is shown in figure 2-2.

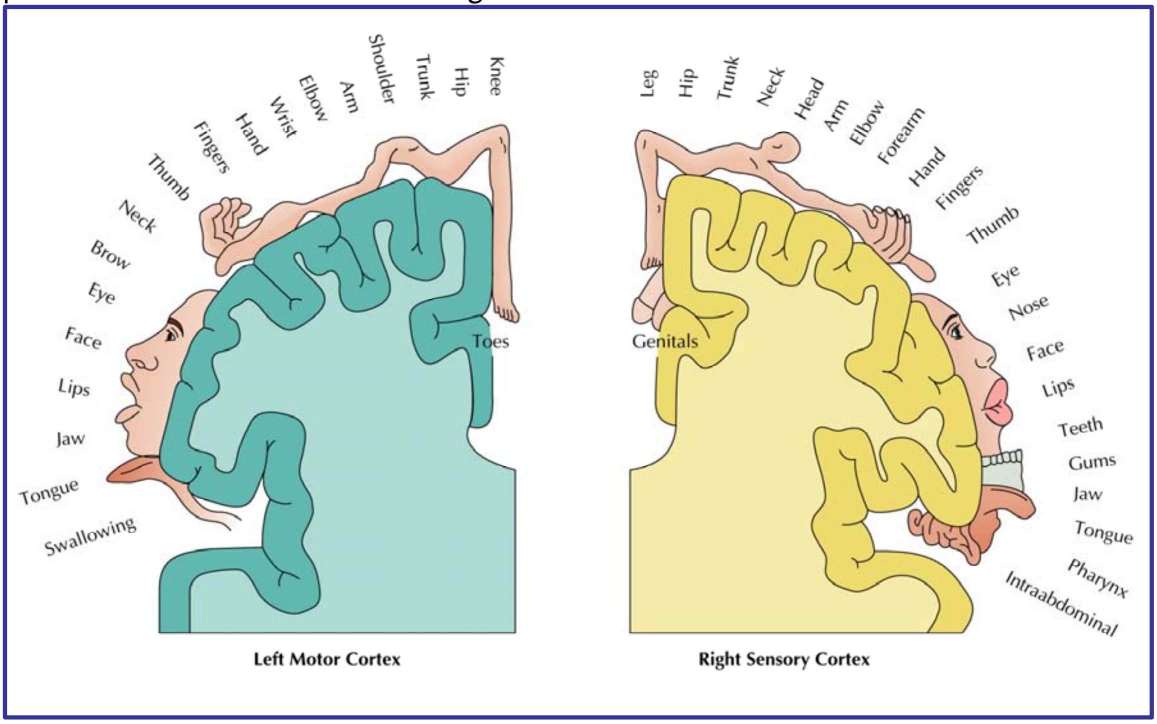


Figure 2-1 Diagrammatic representation of the somatosensory mapping to the cortex. Diagram represents a sagittal section through the left and right cortex through the region representing somatosensory inputs. The sizes of the different pieces of the body are scaled to represent their relative importance(6).

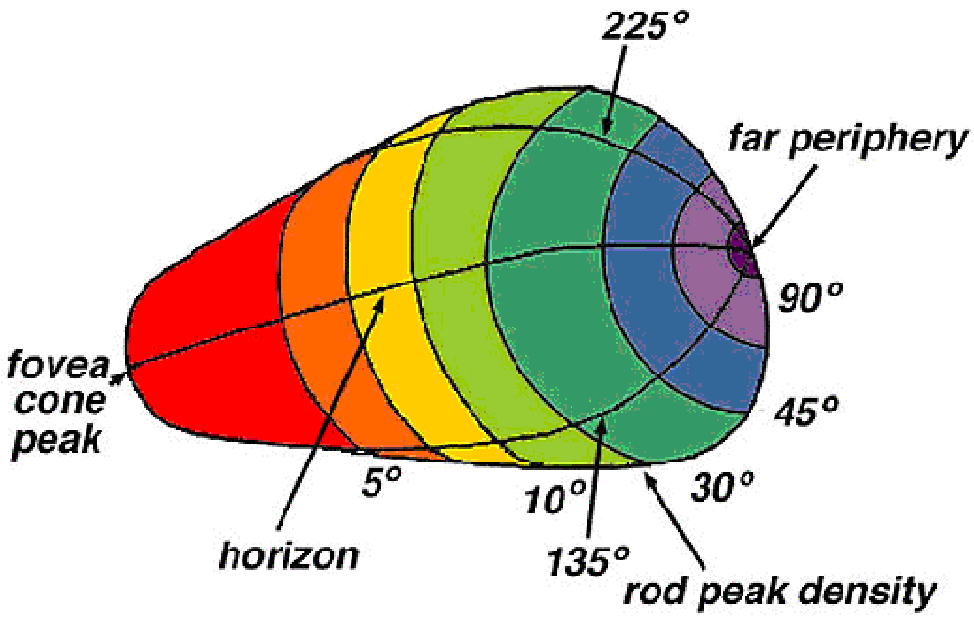


Figure 2-2 Relative representation of the visual field in the cortex(6).

A minimal requirement for visuo-tactile integration is that the signals arising from the two separate modalities be assigned a common spatial origin. This implies that the signals generated in one modality need to be recoded in the frame of reference of the other modality, or alternatively that each modality is recoded into a single and separate abstract frame of reference. How this is achieved is still an area of active research and not understood.

Furthermore, the whole integration process is perforce dynamic. The retinal location of a tactile stimulus will shift whenever the hand is moved or a change of gaze occurs, therefore the mapping of spatial coordinates must be continuously updated. There is neurophysiological evidence for transformations of coordinates on the parietal and premotor multimodal areas [21], 22] as well as computational theories [23] as to how these might operate.

2.3 Psychological Models

A number of psychological models exist to explain experimental studies into attention allocation within a multisensory environment. Flexible limited capacity models propose attentional resources are allocated through a central pool. Multiple resource theories on the other hand propose that there are several resources and within each of these we can allocate attention separately [24, 25]. Resources represent the mental effort supplied to improve the processing efficiency or the performance of a mental operation. Their deployment is under voluntary control and they are scarce [26].

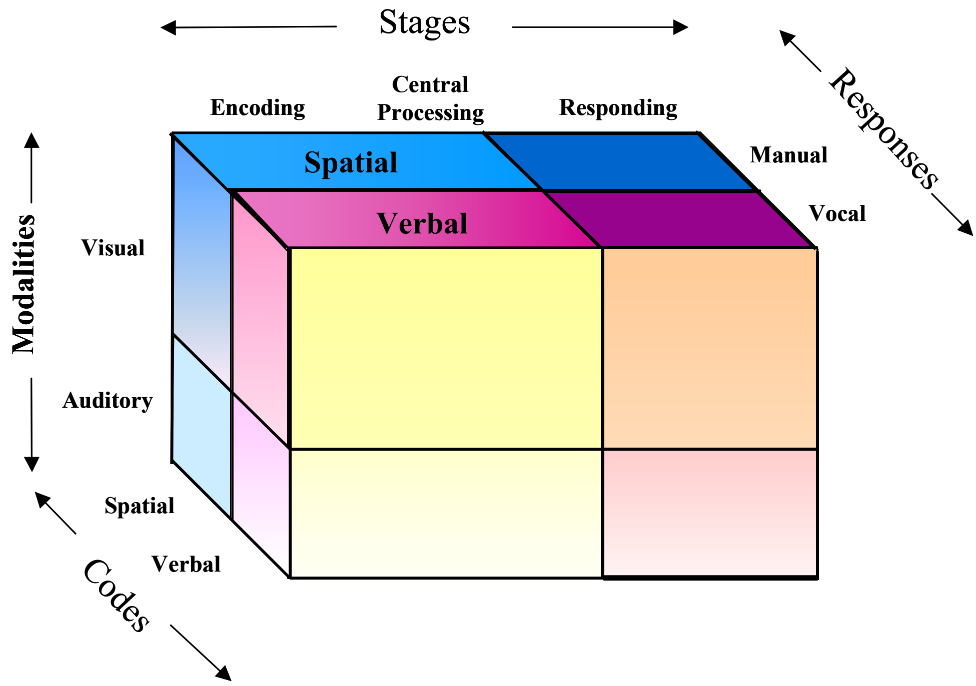


Figure 2-3 Wicken's multiple resources model.

Tasks, to be performed concurrently, will interfere more if more resources are shared. Wicken's model [25] tries to account for the allocation of attention and the processing of information in complex tasks, such as piloting an aircraft, in which the operator works in a high-workload environment and has difficulty processing all the information. Figure 2-3 presents this model, in which resources are defined by three

relatively simple dichotomous dimensions: two resources defined by processing stage (early versus late processes), two modality-defined resources (auditory versus visual encoding), and two resources defined by processing codes (spatial versus verbal).

In the *stage* dimension, the resources used for perceptual and central-processing activities appear to be the same, and they are functionally separate from those underlying the selection and execution of responses. The two perceptual *modalities* are distinguished to account for the possibility to divide attention between two senses such as the eye and the ear for example, which is easier than between two auditory channels or two visual channels. The degree to which peripheral rather than central factors are responsible for better cross-modal time-sharing than intra-modal is uncertain. The *code*-related resource dimension may be defined, in part, by the two cerebral hemispheres: spatial processing taking place mainly in the right hemisphere and verbal processing mainly in the left hemisphere [26]. With respect to the codes for information processing, two principles of stimulus—central-processing—response-compatibility are conveyed. Verbal tasks seem to be best served by auditory inputs and speech responses, whereas spatial tasks seem to be best served by visual inputs and manual responses [25, 27].

The multiple-resource theory of Wickens provides a good framework that summarises a lot of experimental data on dual-task performance. However, it does not encompass all possible effects in dual task performances, such as switching, confusion and cooperation [28]. The interplay between cognitive processes proves to be rather complex and the “simple” attribution of cognitive tasks to a small number of resources addresses this interplay only partially.

2.4 Related Tactor Work

Young et al [29] investigated the effect of cross-modal links in attention between haptics and vision using a 2 x 2 tactile display in a seat back, to cue a 4-quadrant visual search task. In this single task design, subjects were instructed to identify the target quadrant as soon as they noticed it, either with or without the aid of tactile cues. Furthermore, the experimenters employed two conditions of tactile stimulation, one in which there was 80% agreement of the tactile cues with the visual representation and another in which there was only 20%. Subject performance on the task was measured by recording the reaction time to correctly identify the target quadrant.

The experimenters found that, in the 80% agreement condition, the subjects were able to consistently improve reaction time performance over the no tactile cues baseline. Performance was more variable in the 20% agreement condition. Young et al noted that subjects exhibited positive, negative or no haptic cueing effects. From these results the authors concluded that vibrotactile cues to orient visuo-spatial attention are intuitive but not involuntary.

Lindeman et al [30] investigated the effects of adding vibrotactile information to performance on a visual search task. In a similar apparatus to experiment above, the experimenters utilised a 3x3 array of tactors in a seat back to deliver tactile information to the subject. Subjects were required to locate a target letter on a screen of three blocks of 8 randomly organised distractor letters. The conditions encompassed a variety of different visual cueing conditions, with or without tactile aids, and then a baseline condition in which subjects performed the letter search task without any aids. Performance was measured by the reaction time to correctly identify the target letter.

The experimenters found that visual cueing was the most effective performance enhancing measure, although tactile cueing also significantly improved performance over the baseline. However it was noted in the discussion that the tactors used in this trial were pager motors. These have a slight time delay between activation and reaching the acceleration levels required to take the stimulus supra-threshold. Compared to the virtually instantaneous response to visual cueing, this time delay might have been expected to affect the results in the tactile cueing conditions.

2.5 Summary

In summary, the literature is clear that congruent tactile stimuli can improve performance on search tasks. However, the results from these experiments, whilst useful, are limited in the extent to which they can be applied to the some of the proposed real world applications of tactor technology in high workload situations. They typically involve trials with one task, from which the subject is not expected to divert his/her attention at all.

Furthermore it is clear that multisensory integration can be viewed and interpreted as a “low-level” sensory process or a “high-level” cognitive process.

Overall, this would suggest that there is a need for further research into visuo-tactile interactions and integration, with emphasis on simulations of high workload tasks.

3 Experiment One

3.1 Introduction

3.1.1 Aim

The aim of this preliminary experimental program was to conduct trials to ascertain the influence of congruent and incongruent tactile-visual information on performance during an abstraction of a real cockpit environment.

The results of this scoping study could be used to direct a future program to systematically investigate the multi-sensory integration and quantify the benefit to a pilot's ability to maintain correct spatial orientation, that is, to avoid unrecognised SD, and recover from recognized SD; most importantly to identify when multi-sensory information may be of a benefit to or hinder pilot spatial orientation in-flight.

3.1.2 Objectives

The objectives of this preliminary research programme were to: -

- Determine experimentally whether, and by how much, a tactile signal can benefit an individual carrying out a high workload visual task.
- Determine and quantify the effects of congruent and incongruent tactile-visual information on performance.
- Ascertain if any beneficial effect is as a result of true multisensory integration or whether it is a simple alerting (attention grabbing) effect.

3.2 Apparatus

Vibrotactile stimulation was delivered with two EAI Acoustics C2 tactors. They were 30mm in diameter, 10 mm deep, and weighed 17g. Each tactor contained a 8mm-diameter contactor. The tactor is capable of producing displacements in excess of 5.8mm into most skin sites.

Two tactors were mounted on a belt in such a way that that they rested on the subjects oblique muscles (approximately 150 mm from the umbilicus). During the study there was no variation of the amplitude of the tactor signal. If used, a tactor was activated for a 1 second period at full displacement amplitude. The experimental study was carried out using a Dell™ laptop computer, which managed presentation of the visual tasks, controlled the tactors via a custom controller using a parallel port interface and recorded subject responses.

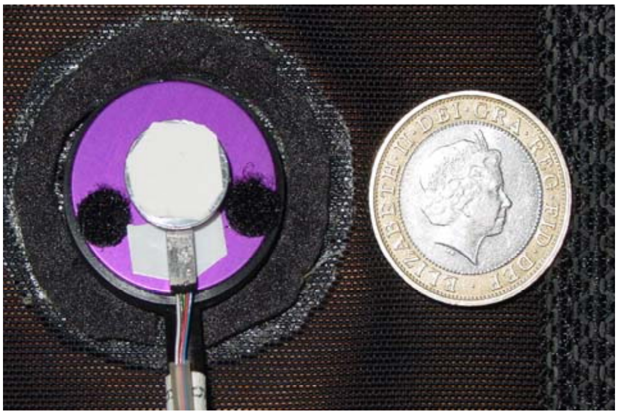


Figure 3-1 A photograph of the EAI C2 stimulus delivery tactor with a UK £2 coin for size comparison. The tactor also has an accelerometer mounted on it, for use in other experiments into the effects of whole body vibration on tactor threshold sensitivity.

3.3 Subjects

Eight subjects, five female, and three male, (mean age 29.6 years, standard deviation 7 years) participated in the experiment. They were chosen at random from staff in the Centre for Human Sciences. All had either normal or corrected to normal vision and were naïve to the purpose of the experiment. The experiment was conducted under a generic protocol approved by the QinetiQ Ethics committee. Subjects provided written consent to take part in the experiment

3.4 Methods

A visual task was developed which was an abstraction of the tasks undertaken by a pilot and which contained two elements. The first was a tracking component, which corresponded to the pilot maintaining the aircraft in safe flight or a secondary target-tracking task for example. The second component was a high demand cognitive task, which represents the many other tasks a pilot might undertake in a high workload situation.

Subjects were required to divide attention between two visual tasks and provide responses to both simultaneously. They were required to maximise their performance on both elements of the task. The schematic diagram in figure 3-2 below illustrates how the task appeared to the subjects. The visual-tracking task was in the lower half of the screen, and the alphabet based high-demand cognitive task was in the upper half of the screen.

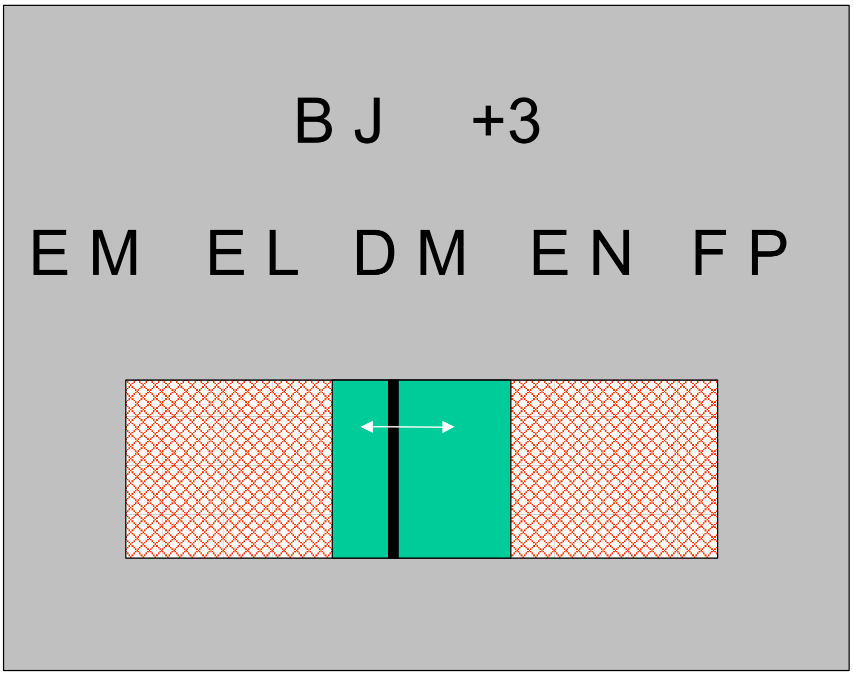


Figure 3-2. A diagrammatic representation of the visual task undertaken by the subjects. In this example the letter offset is positive (+) and is a numerical offset of 3.

Tracking Task: The lower half of the display contains a rectangular box region containing a central green area and two separate red regions on either side. During the experiment a vertical black line moved left and right horizontally in a semi-random manner (a normally distributed random number generator modulated a deterministic left-right oscillation). The line could move within the whole extent of the rectangular box region. The subject was instructed to ensure the line did not enter the red "danger zones" on either side of the central green ("safe") region. If the line did move into these zones, the subject was required to reset the line to the centre of the green zone using the appropriate reset buttons on the laptop keyboard, assigned to the Z and X keys respectively. Response time was a key measure in this experiment; therefore subjects were instructed to rest the index and middle fingers of the left hand on these keys throughout the experiment, so that psychomotor influences were kept to a minimum. (We stress that this is not a tracking task in the traditional sense. Subjects were not required to maintain a cursor or other marker on the bar as it moved. Only deviations across the two boundaries and the time taken to cortrect them were recorded).

Alphabet calculation distance task: The upper half of the display contains a cognitive task. It was a five alternative forced choice. The subject is initially presented with a letter pair at the centre-top of the display. To the right of the letter pair was a number with a sign (either positive or negative). Below the letter pair were five pairs of letters. The subject was required to compute the alphabetic offset from the test letters by the amount indicated by the sign and number on the right and then choose from the five options presented under the test letter pair. Thus, in figure 3-2 above, the correct response is the letter set **EM**, which is +3 letters away from BJ. The subjects indicated their choice by clicking the mouse on one of the five options. The subject had a limited time to perform this task (15 seconds). As soon as the subject chose a letter pair or at the end of the time period a new letter pair and a different sign and offset was presented. The letter task thus ran continuously and

independently from the tracking task. The subject choice of letters was recorded, or if the time expired the event was recorded as a "miss".

The baseline experiment was the situation where the subject carried out the two tasks explained above with no other input. Two additional conditions were used to investigate to what extent vibrotactile information could be used to enhance performance or reduce error rate in the tracking task during this high-workload situation. Thus three experimental conditions were used:

Condition 0: (None): The tactors were present but were not used in this condition. The subject needed to keep looking at the bar to see if it has gone into the red area.

Condition 1: (Congruent): Whenever the track line reached the red "danger" zone on the relevant side the tactor on the corresponding side of the subject's body was activated. Thus, if the line reached the right side of the green zone the right tactor fired and *vice versa*.

Condition 2: (Incongruent): Whenever the track line reached the red "danger" zone on the relevant side the tactor on the opposite side of the subject's body is activated. Thus, if the line reached the right side in this case the left tactor fired and *vice versa*.

Subjects were given one practice session. This is equivalent to condition 0 above. (In the present experiment, we were interested in whether subjects could make immediate use of the additional information from the tactors, if it was present; therefore no extended training was provided. In a real operational system, possibly containing many tactors it is likely that there will be learning effects and the need for training. Such factors are beyond the scope of the present work). The main experiment consisted of the three conditions detailed above presented in a random order.

The following data were collected in the alphabet task:

- Stimuli: This is the total number of alphabet stimuli presentations in each condition. This number is larger if the subject achieves a higher work rate.
- Correct: The number of correct alphabet decisions in each condition.
- Wrong: The number of incorrect alphabet decisions in each condition.
- Missed: The number of alphabet stimuli presented on which a decision was not made (i. e. it task timed out).
- Reaction time: recorded in seconds for each stimulus presentation.

The following data were collected in the tracking task:

- Stimuli: This is the total number of bar tracking presentations in each condition. This number is larger if the subject achieves a higher work rate as measured by faster resets.
- Correct: The number of correct decisions (appropriate left or right button pressed).

- Wrong: The number of incorrect decisions in each condition (inappropriate left or right button pressed).
- Missed: The number of tracking errors that occurred in which a decision was not made.
- Reaction time: time in seconds to respond to the tracking error.

3.5 Results

The results of the experiment are summarised in the three graphs below. Figure 3-3 shows the mean results for all eight subjects across the data collection categories for the alphabet distance task. Figure 3-4 shows the mean results for all eight subjects across the data collection categories for the tracking task. Figure 3-5 shows the mean reaction time for correct responses to the tracking task averaged across all subjects.

3.5.1 Results: Alphabet Distance Task

Figure 3-3 appears to show very little difference between the three conditions for any of the classification categories. The number of correct responses to the task was slightly lower in the congruent tactor condition. A repeated measures ANOVA was performed on the number of stimuli and correct responses respectively, in order to determine whether any statistically significant difference was evident. The analysis did not show any significant differences. This implies the subjects were maintaining a level of performance consistently across the different tactor conditions, which would imply that the tactor stimulation did not cause a distraction effect in either the congruent or the incongruent condition.

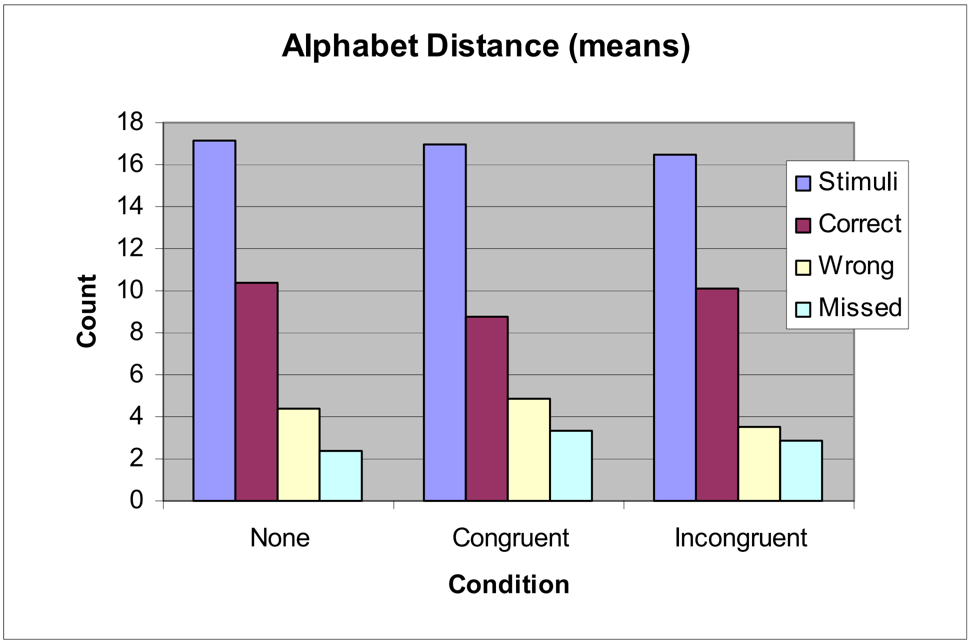


Figure 3-3 Alphabet distance task results. Values are mean counts averaged across all subjects.

3.5.2 Results: Tracking Task

Figure 3-4 shows the results for the tracking task. "Stimulus count" refers to the number of times the bar crossed into the red zone. Correct refers to the number of times the appropriate reset button was pressed. "Wrong" refers to the number of times an inappropriate reset button was pressed, i.e. if the moving bar entered the left zone but the subject pressed the right-hand reset key "Missed" is the number of times the bar entered the red zones and this event was missed by the subject.

The data in the congruent condition appear to suggest that a greater proportion of responses were made correctly than in the case when the tactor input was incongruent. The repeated measures ANOVA revealed a significant effect of experimental condition on the number of stimuli presented [$F(2, 14) = 4.98$, $p <= 0.05$]. A *post hoc* paired comparisons t-test[3] revealed that the number of tracking stimuli (i.e. the number of times the bar entered the 'danger' area) in the congruent condition was greater than during the no tactile condition [$t(7) = -3.416$, $p <= 0.017$].

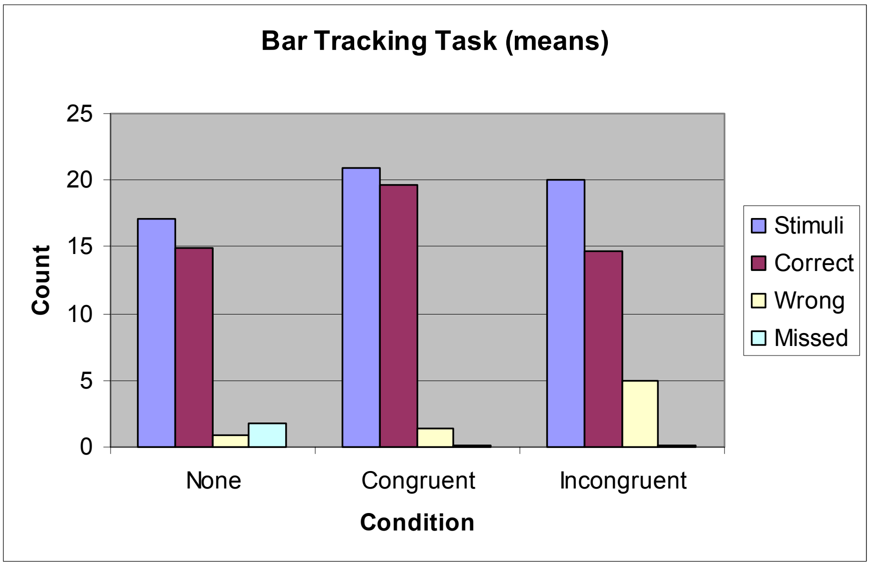


Figure 3-4 Tracking task results. The graph shows the number of stimuli in each condition, the number of times the track error was corrected, the number of times the bar was not corrected and the number missed (i.e. timed out).

A repeated measures ANOVA on the number of correct resets for each category revealed a significant effect of experimental condition [$F(2, 14)=7.686$, $p<=.05$]. A post-hoc paired comparison t-test showed that the number of correct resets was greater for the congruent condition compared to the no tactile condition [$t(7) = -3.225$, $p <= 0.017$].

A repeated measures ANOVA for the number of 'wrong' responses, showed a significant effect of experimental condition [$F(2, 14) = 6.197$, $p <= 0.05$]. A *post hoc* paired comparison t-test revealed that the there were more wrong responses in the no tactile condition compared to the incongruent condition [$t(7) = -3.351$, $p <= 0.017$].

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[3] *Post hoc* t-tests used a simple Bonferroni correction, i.e. (α/n) where α is the *a pri*ori significance level.

The repeated measure ANOVA was also applied to the 'missed responses' category, when subjects failed to carry out a reset operation. A significant effect of experimental condition was found [F(2,14) = 10.658, p <= 0.05]. The *post hoc* paired comparison t-test revealed that the were significantly more missed stimuli in the absence of tactile condition than in either of the congruent or incongruent conditions [t(7) = 3.529, p <= 0.017] [t(7) = 3.265, p <= 0.017].

As well as analysing the raw data for each category, it was also decided to compare the percentage correct as a function of the number of stimuli presented. These percentages were then put through repeated measures ANOVA, with a *post hoc* paired comparisons t-test if any significance was found.

3.5.3 Results: Tracking task – Percentage Correct

The repeated measures ANOVA revealed a significant effect of condition (F(2, 14) = 6.107, p <= 0.05). The *post hoc* paired comparison t-test showed that the significant difference occurred between the no tactile condition and the incongruent condition (t(7) = 3.124, p <= 0.017). The difference between the congruent condition and the incongruent condition approached significance with a p value of .029. Performance was certainly more consistent on the congruent condition than on either the incongruent or no tactile condition, as can be seen from the low standard deviation (4.88).

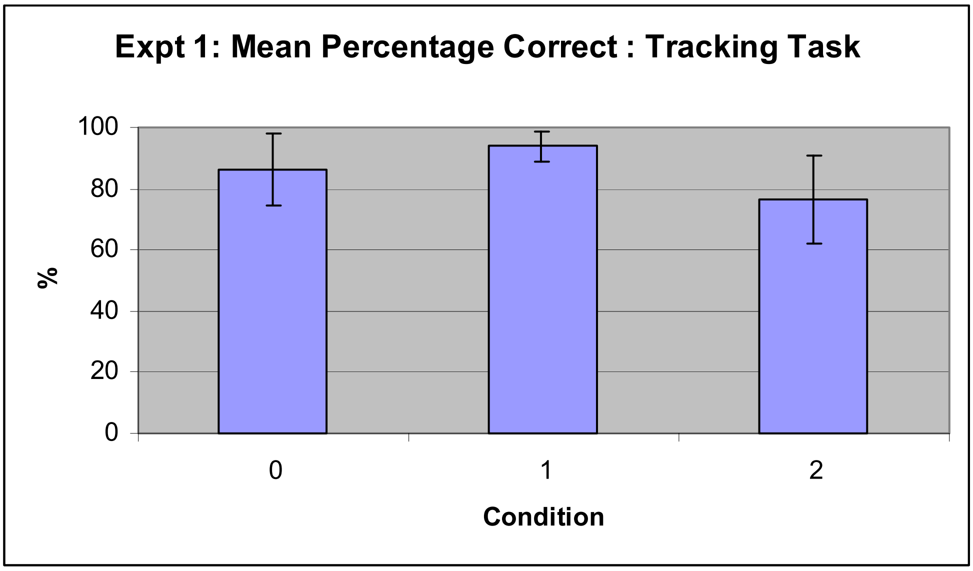

Figure 3-5 Graph showing the percentage of correct responses averaged across subjects for the tracking task. Error bars represent +/- 1 standard deviation of the mean.

3.5.4 Results: Alphabet Distance Task – Percentage Correct

The repeated measures ANOVA revealed no significant effect of condition. There were no significant differences between the percentages correct for any of the conditions. In terms of percentage correct, subjects responded equally well across all conditions, although there was a wide degree of variability amongst different subjects' performance.

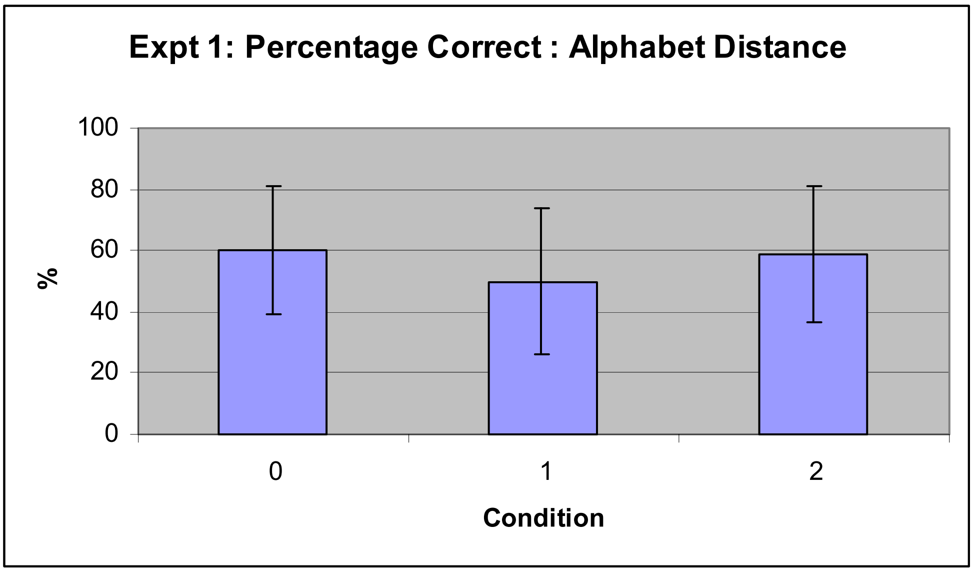

Figure 3-6 Graph showing the percentage of correct responses on the Alphabet distance task. Error bars represent +/- 1 standard deviation of the mean.

3.5.5 Results: Reaction Times

A graph of the reaction times for correct responses to this task can be seen below (figure 3-7). Clearly responses are much faster for both of the conditions involving the tactors. The same procedure was applied to the reaction times for correct responses, where there was a significant effect of condition [$F(1.08, 7.56) = 13.411$, $p <= 0.05$ Greenhouse-Geisser]. *Post hoc* testing revealed greater reaction times for the no tactile condition compared to the congruent condition [$t(7) = 4.029$, $p<= 0.17$] and greater reaction times for the incongruent condition compared to the congruent condition [$t(7) = -4.909$,$p <= 0.017$].

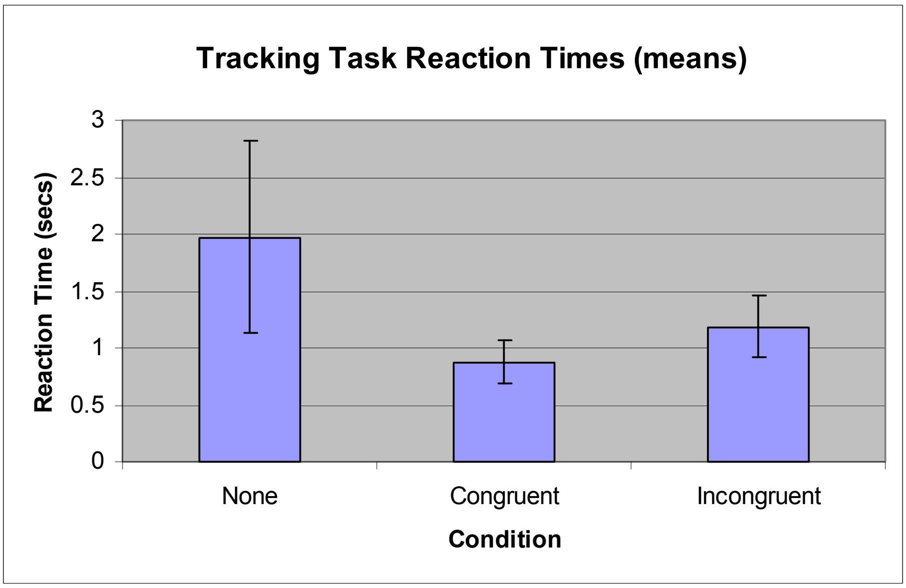

Figure 3-7 Reaction times for the tracking task. Error bars indicate +/- one standard deviation of the mean.

3.6 Discussion of Experiment One

The aim of this first experiment was to ascertain whether providing a somatosensory stimulus cue to a background-tracking task would improve performance of the task under a high cognitive workload situation. In addition the experiment investigated whether the lateralisation of the cue influenced performance.

It is interesting to note that there were no significant differences in performance on the alphabet distance task between the different conditions, although the visual tracking task showed significant variation. Subjects responded significantly more quickly to the stimulus in both the active tactor conditions. As expected, the vibrotactile interface proved to be an aid in speed of response. Furthermore, the response time was significantly faster in condition one, the congruent condition, than in the incongruent condition two. It can also be observed from the low standard deviations in these conditions that subjects were *consistently* faster at responding, as opposed to condition 0 when there was no vibrotactile stimulation, where response times were higher and more variable.

The faster response times in the vibrotactile conditions meant that more repetitions could be presented; hence there were significantly more stimuli presentations in the congruent condition compared with the no tactor control condition. The number of stimuli also went up in the incongruent condition, although not significantly. There were significantly more correct responses in the congruent condition compared with the control condition, but this significant difference was not present between the no tactor control and the incongruent condition. The larger number of wrong responses in the incongruent condition potentially indicates that the tactor cue proved to be strong enough that it could not be ignored in high workload situations; in some cases subjects appeared to instinctively use the tactor cue even though it contradicted the visual information. This effect suggests that subjects were using the lateral nature of the tactor stimulus to automate their decisions on the tracking task.

In summary, this experiment suggests that:

- Vibrotactile interfaces aided subjects to make faster responses to the visual tracking task.
- Responses in the congruent condition were more likely to be correct than in the incongruent condition.
- Optimised tactor usage enables visual tracking task performance to improve without any degradation in alphabet distance performance.

These results are easier to understand in a higher-level cognitive framework, than in a multisensory integration one. The tactors are removing from the visual domain a proportion of the work the subject must undertake. Because the somatosensory input can process and drive the required response without visual intervention there is a greater ability to concentrate on the visual alphabet task. This is probably not surprising since only two tactors were used and these mapped clearly onto two motor responses. Patterns of behaviour may be rather different if more complex patterns of tactor stimulation are used and the task is not so clearly lateralised.

4 Experiment Two

4.1 Introduction

In the first experiment it was found that the congruent tactors were able to improve performance on the tracking task. However it was not clear how much of this improvement in performance was due to the attention diverting component characteristic of vibrotactile stimulation, and how much this was due to actual decisions being taken purely on the vibrotactile information source. An experiment was therefore designed to disambiguate these possibilities.

4.2 Objectives

In the second experiment an alternative condition was introduced. In this condition, both tactors activated together when the tracking bar entered the red area at either side. This condition alerted the subject to the tracking bar status, but did not convey any direct information about the side that needed to be reset. Performance in this condition can then be compared with performance in the congruent condition in which the subject was alerted to the tracking bar's status *and* the side that needed to be reset. The effect of the information component of the vibrotactile stimulus on performance on the bar task could then be assessed.

4.3 Apparatus

The apparatus was identical to that used in experiment one.

4.4 Subjects

Twelve subjects took part in the experiment. They were chosen at random from staff in the Centre for Human Sciences. There were seven female and five male subjects (mean age 26.1 years, standard deviation 5.5 years). All had either normal or corrected to normal vision and were naïve to the purpose of the experiment. The experiment was conducted under a generic protocol approved by the QinetiQ Ethics committee. Subjects provided written consent to partake in the experiment.

4.5 Methods

The general method was the same as that used in experiment one. The conditions were:

Condition 0: (None): The tactors were not used in this condition. The subject must keep looking at the bar to see if it had gone into the red area. This condition was used as a baseline as in the first experiment.

Condition 1: (Congruent): Whenever the track line met the red "danger" zone on the relevant side the tactor on the corresponding side of the subject's body was activated as in experiment one.

Condition 2: (Dual): Whenever the track line met the red “danger” zone on either side, both tactors were activated together, thereby alerting the subject to the state of the tracking bar, but not to which side the bar was on.

4.6 Results

The results of the experiment are detailed in the three graphs below. Figure 3-8 shows the mean results for all twelve subjects across the data collection categories for the alphabet distance task. Figure 3-9 shows the mean results for all twelve subjects across the data collection categories for the bar task. Figure 3-10 shows the mean reaction times for correct responses to the bar task.

4.6.1 Results: Alphabet Distance Task

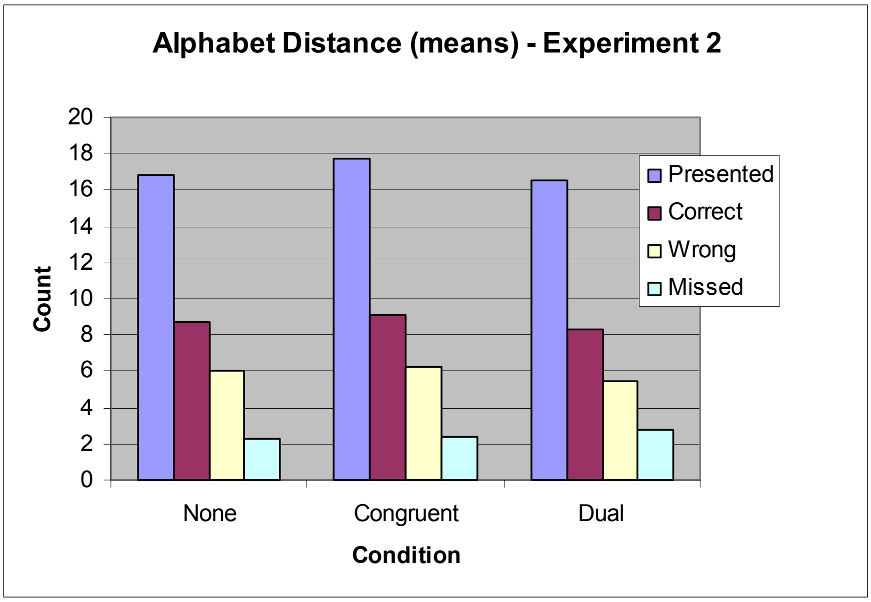

Figure 3-8 Results from alphabet distance task. Values plotted are mean counts averaged across subjects.

The results for the alphabet-tracking task are shown in figure 3-8. The legend is the same as in figure 3-3. The results show very little difference between the three conditions for any of the classification categories. A repeated measures ANOVA was performed on the data. This did not reveal any significant differences. The lack of any significant difference between any of the conditions indicates that the subjects performed equally well on the alphabet distance task for all conditions as in the first experiment.

4.6.2 Results: Tracking Task

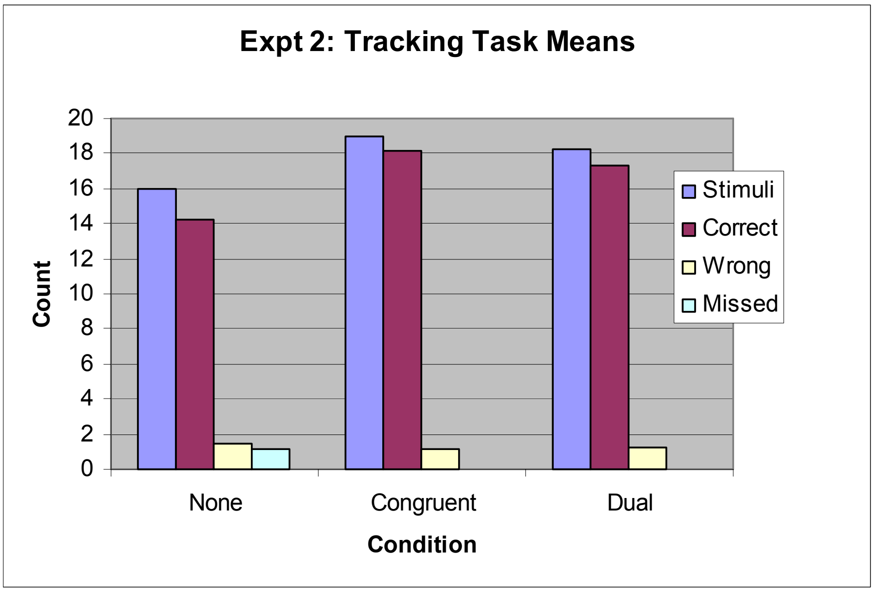

Figure 3-9 Results from visual tracking task (Experiment 2).

Figure 3-9 shows the mean scores for all subjects across the three of conditions. A repeated measures ANOVA was used to test for any differences between each condition.

There was a significant effect of experimental condition on the number of stimuli presented [F(2, 20) = 5.175, p <= 0.05]. *Post hoc* paired comparisons t-tests[4] revealed that the significant difference occurred between the no tactor control condition and the congruent tactor condition [t(10) = -2.849, p <= 0.017]. There was no significant difference between the congruent condition and the dual tactor condition however, or between the no tactor condition and the dual tactor condition.

There was also a significant effect of experimental condition on the number of correct responses to the visual tracking task [f(2,20)=7.097, p<=.05]. *Post hoc* paired comparison t-tests showed that the significant difference occurred between the control no tactor condition and the congruent tactor condition [t(10) = -3.2 p <= 0.017]. The differences between the no tactor control condition and the dual tactor condition, and between the congruent tactor condition and the dual tactor condition were not significant.

There was no significant effect of experimental condition on the number of wrong responses. For this experiment the mean number of wrong responses for each condition was low: 1.45 for the no tactor control, 1.18 for the congruent condition and 1.27 for the dual condition. The only missed responses occurred during the control condition; therefore no statistical analysis was carried out.

[4] Bonferoni corrected as in Experiment one.

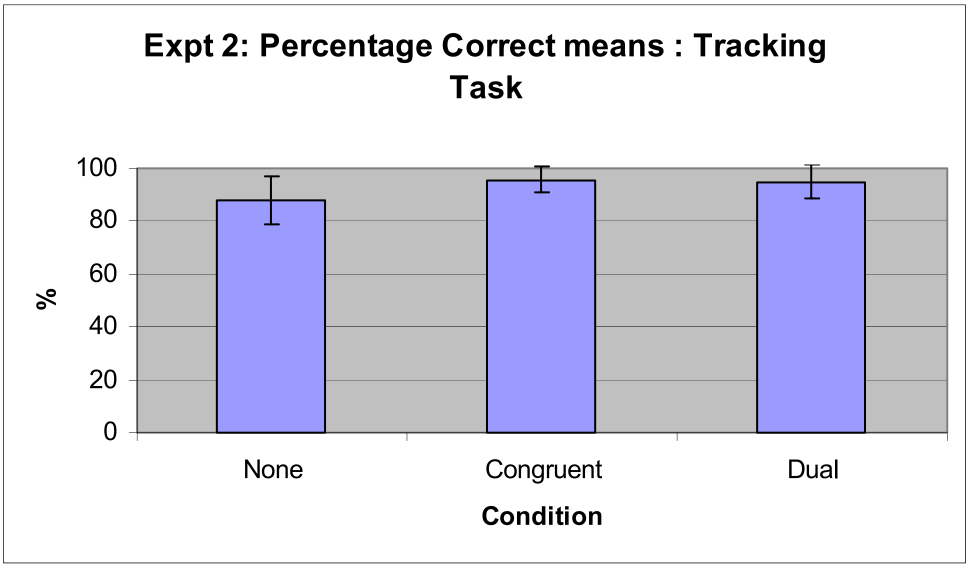

Figure 3-10 Graph showing the percentage of correct responses on the tracking task. Error bars indicate +/- one standard deviation of the mean.

The repeated measures ANOVA showed a significant effect of condition on the percentage of correct responses (F(2,20) = 4.112, p <= 0.05). However, a *post-hoc* paired comparison failed to show any significance. It is suggested that the significant difference identified by the ANOVA would have occurred between the no tactile condition and the congruent condition (p = 0.046), however the paired comparisons t-tests lacked the required discrimination.

4.6.3 Results: Alphabet Distance Task

As in experiment 1, there was no significant effect of condition on the percentage of correct responses on the alphabet distance task.

4.6.4 Results: Reaction Times

The mean reaction times for each condition can be seen in figure 3-12 below. A repeated measures ANOVA showed a significant effect of experimental condition [F(2,20) = 8.22, p <= 0.001]. *Post-hoc* paired comparisons revealed significant differences between the control condition and the congruent condition [t(10) = 3.446, p <= 0.017] and between the control condition and the dual condition [t(10) = 4.012, p <= 0.017]. There was no significant difference between reaction times for the congruent condition and the dual condition.

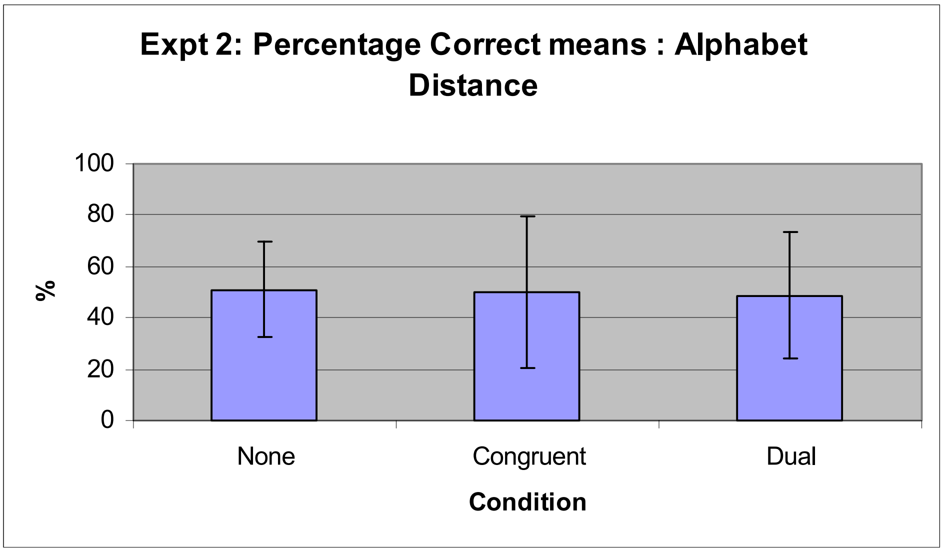

Figure 3-11 Graph showing the percentage of correct responses on the alphabet distance task. Error bars indicate +/- one standard deviation of the mean.

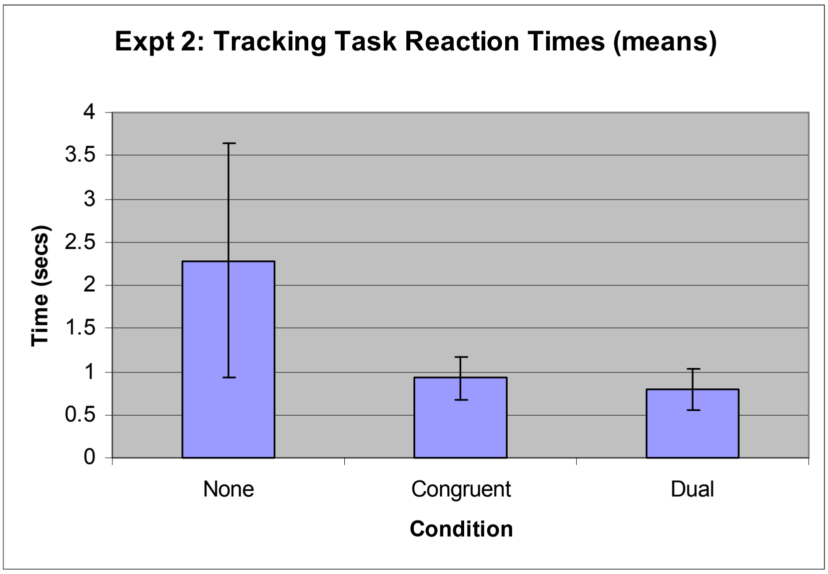

Figure 3-12 Tracking task reaction times for Experiment 2. Error bars indicate plus and minus one standard deviation from the mean.

4.7 Discussion of Experiment Two

Qualitatively the results from the second experiment resemble the results from the first experiment. In particular, performance was maintained in the alphabet task under the different conditions and differences were observed in the reaction times, both in terms of absolute value and variability. This similarity is broadly supported by the statistical analysis.

The purpose of the second experiment was to disambiguate the attention effects of the tactors from the integration of this signal with the visual information. The similarity of results, i.e. that similar effects were found with a dual tactor stimulus as

with the previous experiment provides strong support for the attention “grabbing” hypothesis rather than any lateral cuing by the tactor system.

5 Conclusions and Recommendations

5.1 Conclusions

To reiterate, the objectives of this preliminary research programme were to: -

- Determine experimentally whether, and by how much, a tactile signal can benefit an individual carrying out a high workload visual task.
- Determine and quantify the effects of congruent and incongruent tactile-visual information on performance.
- Ascertain if any beneficial effect is as a result of true multisensory integration or whether it is a simple alerting (attention grabbing) effect.

We have used a simulation of a pilot activity in order to investigate these issues. The results have demonstrated that presenting a tactile stimulus to subjects whilst undertaking visual tasks does not distract them from the main visual tasks. This is evidenced by the maintained performance in the alphabet distance task, across all of the experimental conditions.

A tactile stimulus does, however, provide a benefit in terms of response time in reacting to the tracking task. Response times with tactor support were approximately twice as fast compared with no tactor support.

In addition, there was a much-reduced variability in response times with tactor support compared with none.

Small differences in congruent and incongruent tactor support were observed in the data from the first experiment. The second experiment demonstrated however that the main effect of the tactor was to act as a cue to the track being lost, i. e. as an attention grabbing mechanism. There was no direct benefit of the particular lateralisation of the cue.

Overall the results suggest that subjects were able to increase capacity and performance on the tracking task without any detriment to the high demand cognitive task when tactor cueing was used.

The results support the concept of using a tactor system as a method of aiding a pilot by reducing workload and improving performance and reaction times. Tentatively, the results suggest that tactile systems may reduce the risk of pilot spatial disorientation by two methods. Firstly, by reducing workload and improving performance on a secondary task (e.g. target acquisition), thus minimising distraction from the primary flying task. Secondly, by providing an attention-grabbing mechanism for pilots who have become spatially disorientated and are unaware of the fact (Type I SD). However, there are still may human factors issues regarding the integration of tactile systems for pilots that require further, systematic investigation.

5.2 Recommendations

5.2.1 General

The study has identified that there is a potential quantitative benefit in using tactors to provide cuing information in a simulation of a high workload environment. The study was very much an initial study and there is considerable scope for further research work. Some of the areas we believe that are worth investigating are discussed in the following sections.

5.2.2 Effects of different parameters

The study only investigated very simple somatosensory system stimulation yet showed a significant response time benefit, albeit in this simplified task. Many studies are currently investigating far more sophisticated systems consisting of arrays of tactors. In order to ascertain the effectiveness and highlight any potential detrimental effects of tactile orientation/information aids on pilot spatial orientation, further work should build on the findings of the current scoping study by investigating the following:

- Congruent versus incongruent complex patterns of information in low and high workload situations. E.g. orientation information provided in tactile modality, target acquisition in visual modality. Questions to be answered include:
    - Is the tactile orientation information still attended to when moving from low to high workload situations? Is it any better in this situation than visual information alone?
    - What is the effect of time on task? Can tactile information still be attended to without effort, in high workload visual situations that last for tens of minutes especially if this information is incongruent? Is the tactile information 'tuned out' after a while? If this is the case does the amplitude/frequency/pattern of the tactile stimuli need to change?

In addition to these specific questions there is a need to understand the influence of a number of factors on the optimal way of conveying tactile orientation information to the pilot including:

- Tactor location
- Tactor Vibration Frequency
- Tactor Amplitude
- Tactor spacing
- Effects of whole body vibration (note here that we have completed an initial programme of work on this)
- Effects of auditory inputs – either noise or significant signals

5.2.3 Brain Activity Correlates

A key factor associated with the efficacy of using tactors, as a mechanism for augmenting the situation knowledge of pilots is the ability to direct the attention of

the wearer. Simple threshold measures of tactor activation provide an indication of sensory activation and perception, however we have not as yet examined the potential for cortical gating of the sensory input. The key question is how easily is tactor activity ignored? This question becomes particularly salient at periods of high workload where sensory gating could mean that an important source of information is ignored. To address this question directly it is proposed that the steady state evoked brain response be examined. Steady-state responses (SSRs) are frequency following responses evident in the electrical activity of the brain. Crucially SSRs are attention dependant, thus if two stimuli are presented at different frequencies, the stimuli that is attended to will be augmented whilst the non-attended will be attenuated.

5.2.4 Saccadic Eye Movements

The traditional mode of response speed assessment has been to measure the time it takes to press a button, usually by a finger or a foot movement. It is now relatively easy to measure *saccadic reaction time*, i.e. the time from the presentation of a stimulus to the beginning of the eye movement to a target. We do not know whether providing a somatosensory stimulus aid modifies eye movements. This may be significant in a complex environment such as a cockpit.

5.2.5 Overall Recommendation

This study used a set of tasks, which were a significant abstraction of the real tasks that a pilot must undertake. Because a simple design was used, the results were easy to interpret. It is clearly important to determine whether such benefits still occur in a real task, since the diversity and complexity of flying an aircraft might negate the benefits seen here. Moving to a flight trial would not only be costly but also means that the experimental control and rigour is reduced.

We propose therefore that a useful compromise would be to make use of the Cognitive Cockpit facility [31] within the Centre for Human Sciences. This cockpit has been developed by fusing a number of technologies including the real time

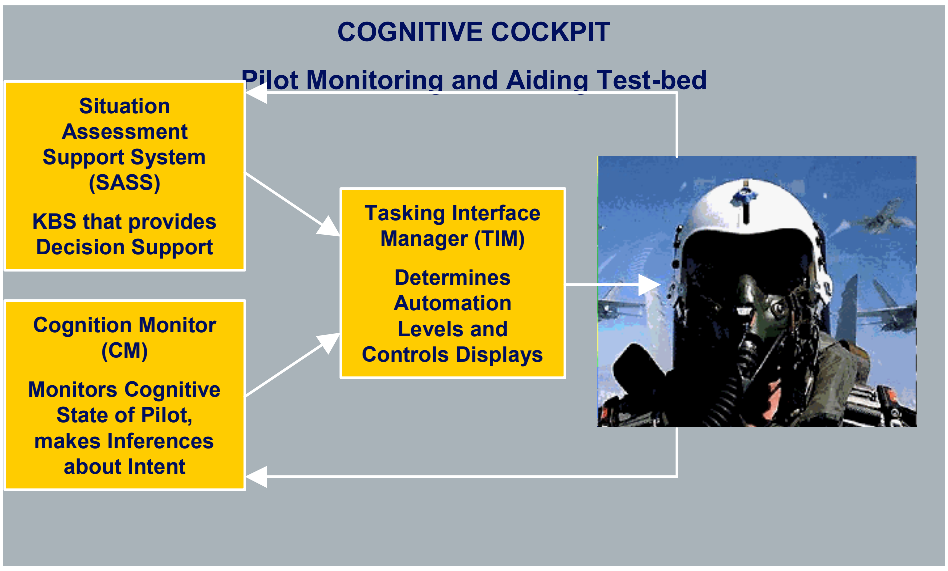

Figure 5-1 Overview of Cognitive Cockpit Environment

estimation of cognitive-affective status derived from tracking physiological and behavioural measures, the implementation of a decision support system, and a framework for the implementation of adaptive automation and task scheduling. These are implemented using principles of cognitive engineering through a number of adaptive interfaces. A closed-loop trial was recently completed (November 2003) during which the stability and performance of the system was examined under different levels of threat/workload in a realistic deep-strike mission. Using this environment would allow a number of aspects – realism of task, high workload environment, monitoring of brain activity, time on task and complex pattern of information – all to be investigated with a single controlled experimental environment.

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A Psychophysical Vibrotactile Perceptual Threshold Methods

This annexe summarises some of the key experiments on tactor thresholds. Reference citations refer to the bibliography.

Author	Type	Description of method
Bolanowski S J Jr, Verrillo RT. (1982). [1]	Modified method of limits	A manual attenuator was adjusted by the experimenter in 2dB steps in a staircase mode sequentially ascending and descending in intensity. The subject's task was to report via a mechanical switch when he/she detects any mechanical event (detection threshold). As the stimulus intensity decreased, a point was reached where the subject could no longer detect the stimulus. The attenuator was then further advanced 2dB beyond this level and an ascending series commenced. During the ascending part, the subject reports where he/she can detect the stimulus. Several series of ascending and descending profiles are repeated (the number of which are dependent on the stability of the subject's response). The threshold is taken as the geometric mean of the detection of the ascending and descending series. Sinusoidal, thenar eminence, 2.9cm^2 contactor. Rise time 10 msec. Interstimulus interval of 1 sec.
Bolanowski et al, 1988 [2] *Zwislocki et al., 1958*.	Forced choice tracking	Subjects judged which two sequential intervals of time contained the test stimulus, by depressing one of two switches. Intervals were separated by 1750 Msec. The stimulus intensity was increased by 1dB for every response error, and decreased by 1 dB for every three correct responses. Hence the criterion used to determine threshold was 75% correct detection over a period of 3 min. The actual period of stimulation was considerably longer than this since the stimulus intensity was always a supra-threshold level prior to each test. Nominally, a period of 3-6 minutes was required before the subject reached the approximate threshold level at which time the 3-min period of 75% detection was started.
Craig, 1972 [3]	Modified Method of Limits	To gain an absolute threshold, VT sensation was raised to a 14-, 21-, 28- or 35-dB sensation level. Subject depressed a button to start the trial, which was followed 1000msec later by the first stimulus, followed by the second 1000msec later. Subject was asked to depress the appropriate button to indicate which was more intense than the other. Feedback given by light indicator.

Craig, 1972 [3] *Campbell, 1962*	Forced choice for detection of difference thresholds	Four trials constituted a block. When subject gave 4 correct responses out of 4 trials, the difference between the two signals was reduced by 0.3dB – i.e. the less intense of the 2 stimuli was increased in relative intensity by 0.3dB. 3 correct responses was left unchanged. When subject made 2 or less correct responses, the intensity difference between the stimuli were increase by 0.3dB. Approx. 100 trials (25 blocks) arrive at an estimate of the difference threshold.
Gescheider and Joelson, 1983 [4]	Békésy tracking method	Absolute thresholds: Subjects tracked their thresholds for detecting VT stimuli of 25, 40, 80 and 200 Hz, delivered for durations of 30, 50, etc msecs (this expt investigated temporal summation). Subjects controlled a hand switch to maintain stimulus intensity near threshold. The time interval between stimuli was 1000msec. When the switch was depressed, stimulus intensity decreased by 1.0 dB/sec, and when the subject released the switch, it increased by 1.0 dB/sec. Increases and decreases in intensity over 2-4 mins were recorded, and thresholds derived by fitting a horizontal line through the subject's record.
Gescheider and Joelson, 1983 [4]	Method of magnitude	For ascertaining the intensities that result in an equal sensation of magnitude, subjects had to match the magnitude of the target stimulus on a secondary stimulus, when stimulus duration varied from 30-1000 msec. This comprised two stimuli separated by 1000msec presented every 5 seconds. The duration of the first stimuli was 1000msec, fixed at intensity at 5, 10, 20, 30, or 40 dB above threshold. The duration of the second stimulus was 30, 50, 100, 200, 300, 600 and 1000 msec. Subjects had to equate the sensation of the magnitude by adjusting the intensity of the second stimulus. Closed switch to increased and opened to decrease intensity. When Ss satisfied, measurement taken.
Frisina and Gescheider, 1977 [5]	Békésy tracking method	Sinuosoidal with 1 sec on, 1 sec off, 100msec rise & decay time. Increases and decreases in intensity that resulted in from the subjects' threshold tracking were record as a function of time. Subjects tracked their thresholds for 1-2 mins for each experiment condition. For each stimulus frequency three thresholds were obtained.
Gescheider GA and Wright J.H. (1968). [6]	Method of limits	Subjects tracked threshold response to the 60 Hz stimulus (presented to the fingertip) by depressing and releasing a foot operated switch. When the switch remained depressed, the intensity of the stimulus decreased continuously at a rate of 1dB/sec. When the switch was released, intensity increased at the same rate. 25 msec rise/decay time.

Gescheider et al 1992	Two-interval forced choice (Zwislocki 1958)	2 x 730 msec pedestal (300 Hz) separated by 1000 msec. Signal 300 msec (300 Hz), within pedestal. Pedestal and signal had rise/fall time of 25msec. Observer had to indicate, by pressing one of 2 buttons, in which time interval the signal had occurred. Next trial did not begin until this provided. Signal appeared at random in only one of the two. Amplitude of signal increased by 1dB after each incorrect response, and decreased by 1 dB after every third correct response. Continued until range of signal intensities for preceding 2 mins (about 30 trials) was less than 4 dB. The final threshold estimate was centre of this range. The procedure provides estimate of intensity at which the probability of a correct response is 75%.

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